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The Depths of Hydraulic Fracturing and Accompanying Water Use Across the United States

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* Supporting Information

Reports highlight the safety of hydraulic fracturing for drinking water if it occurs "many hundreds of meters to kilometers underground". To our knowledge, however, no comprehensive analysis of hydraulic fracturing depths exists. Based on fracturing depths and water use for ~44 000 wells reported between 2010 and 2013, the average fracturing depth across the United States was 8300 ft (~2500 m). Many wells (6900; 16%) were fractured less than a mile from the surface, and 2600 wells (6%) were fractured above 3000 ft (900 m), particularly in Texas (850 wells), California (720), Arkansas (310), and Wyoming (300). Average water use per well nationally was 2 400 000 gallons (9 200 000 L), led by Arkansas (5 200 000 gallons), Louisiana (5 100 000 gallons), West Virginia (5 000 000 gallons), and Pennsylvania (4 500 000 gallons). Two thousand wells (~5%) shallower than one mile and 350 wells (~1%) shallower than 3000 ft were hydraulically fractured with >1 million gallons of water, particularly in Arkansas, New Mexico, Texas, Pennsylvania, and California. Because hydraulic fractures can propagate 2000 ft upward, shallow wells may warrant special safeguards, including a mandatory registry of locations, full chemical disclosure, and, where horizontal drilling is used, predrilling water testing to a radius 1000 ft beyond the greatest lateral extent.

INTRODUCTION

The combination of hydraulic fracturing and horizontal drilling has transformed natural gas and oil production in North America. Natural gas production from U.S. shale formations increased from ~5 billion ft^3 (Bcf) per day in 2007 to 33 Bcf per day in 2013 and now provides ~40% of total domestic natural gas production.[1] The production of light oil from shales, tight sandstones, and other relatively impermeable formations in Canada rose from ~0 to >160 000 barrels per day in Saskatchewan, Alberta, and Manitoba alone.[2] A similarly rapid increase in U.S. production of shale and other unconventional oil drove total U.S. production to 9 million barrels per day at the end of 2014, on par with the world's largest oil producer, Saudi Arabia.

One difference between the horizontally drilled, hydraulically fractured wells in North America and conventional oil wells is how quickly production declines. Unconventional oil production in the Bakken of North Dakota drops by 80% or more after the first two years of production.[3,4] Natural gas production in the Barnett Shale of Texas and other unconventional plays declines similarly.[5] A consequence of these steep declines is the need to keep drilling new oil and gas wells; tens of thousands of unconventional wells must be drilled each year in the U.S. to maintain production through time.

Public concerns about the intensity and safety of high-volume hydraulic fracturing have accompanied unconventional oil and gas extraction. Drilling several kilometers underground is now common, accompanied by horizontal distances of 1 to 2 miles (~2−3 km). From 1 to 6 million gallons of water, proppants such as sand, and dozens of chemicals are then pumped underground, often at pressures of >10 000 psi. These pressures are sufficient to crack open the rock formations and allow the gas or oil to flow through the well to the surface. Public concerns over hydraulic fracturing include its water requirements and the potential for drinking-water contamination and surface chemical spills, induced seismicity, and emissions of air toxics and greenhouse gases.[6−20,33]

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Several recent reports examining hydraulic fracturing have concluded that surface activities, particularly spills, and near-surface activities via well integrity provide the greatest potential risks for groundwater, but their risks could be managed with proper safeguards. A report from the U.K. Royal Society and the Royal Academy of Engineering[7] included the following summary: "Concerns have been raised about the risk of fractures propagating from shale formations to reach overlying aquifers. The available evidence indicates that this risk is very low provided that shale gas extraction takes place at depths of many hundreds of metres or several kilometres." The Canadian Association of Petroleum Producers provides a similar description of hydraulic fracturing: "Hydraulic fracturing (also called "fracking") is the process of pumping a fluid or a gas down a well, many hundreds or thousands of meters below ground, to a depth considered appropriate for natural gas production."

One critical assumption behind these statements is an adequate vertical separation between the depth of hydraulic fracturing and the overlying surface aquifers used for drinking water. What defines the "many hundreds of meters" needed to safeguard groundwater from hydraulic fracturing contamination? Davies et al. analyzed vertical fracture propagations for several thousand hydraulic fracturing operations in the United States and found that the greatest upward propagations were 536, 588, and 556 m (~1800 to 1900 ft) in the Marcellus, Woodford and Eagle Ford shales, respectively.[21] Even fractures that do not extend all the way to an overlying aquifer can link formations by connecting them to natural faults, fissures, or other pathways. In British Columbia, a special permit is required if hydraulic fracturing is to occur at depths above 600 m (~2000 ft). Germany's current administration is debating the circumstances under which hydraulic fracturing will be allowed; the April 2015 draft proposal would allow hydraulic fracturing below 3000 m without additional scientific assessments. Unlike examples from Canada, Germany, the U.K., and elsewhere, few U.S. states provide additional oversight for the shallowest hydraulic fracturing nor, to our knowledge, do any states prohibit hydraulic fracturing above a minimum depth.

The goal of this study was to quantify the depths of recent hydraulic fracturing in the Unites States and to analyze the water used for hydraulic fracturing. Using ~44 000 observations of hydraulic fracturing depths reported to FracFocus between 2008 and 2013, we address three questions: (1) What are the range of depths and water use for hydraulic fracturing across the United States?; (2) In which states and at what locations has the shallowest high-volume hydraulic fracturing occurred?; and (3) What policy protections are or might be put in place to minimize the risk of direct contamination of drinking water from hydraulic fracturing? We also examine the policies of different U.S. states for protecting groundwater and compare them to various international safeguards. Finally, we provide some policy suggestions to enhance the transparency and safety of shallow hydraulic fracturing.

MATERIALS AND METHODS

The data in our analysis, collected and made publically available by SkyTruth, were originally reported to FracFocus (fracfocus.org). FracFocus is the "national hydraulic fracturing chemical registry," created and maintained by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission (https://fracfocus.org/welcome). FracFocus is currently used by some states to fulfill requirements for hydraulic fracture disclosure. At the beginning of 2012, only five states · Colorado, Louisiana, Montana, North Dakota, and Texas · required companies to report data to FracFocus. These states comprise ~70% of the observations in the database through 2013; coverage of oil and gas wells in those states should be fairly representative. For other states such as Oklahoma and Pennsylvania where FracFocus reporting is voluntary, the distribution of wells included in the database is neither comprehensive nor representative of all wells drilled in the state. For these reasons, the occurrence of shallow hydraulic fracturing across the United States is underestimated in our analysis.

We downloaded the database on August 5th, 2014 and categorized every well drilled in the United States reported for 2008−2013 using the unique, 14-digit identifiers referred to as American Petroleum Institute (API) numbers. Using the FracFocus database, we compiled the data into a single document and homogenized the API number format to isolate individual wells, removing any duplicate observations. We defined a duplicate as any record having the same API number and the same water reported for fracture use. The concatenation of the API number and the water reported for fracture use was created as a new variable for each record, with 44 392 unique values isolated using this approach. A new table was then constructed to find the appropriate data from the original file for the list of unique concatenated values. Of the 44 392 total well observations in the database, 1918 did not report a vertical depth (classified in FracFocus as "true vertical depth").

All of the observations in the database described here had a reported date of hydraulic fracturing between 2008 and 2013. However, the vast majority (44 363 wells; 99.9% of observations) were hydraulically fractured between 2010 and 2013. Only one well in New Mexico, two wells in North Dakota, five wells in Oklahoma, and 22 wells in Pennsylvania reported a date of hydraulic fracturing in 2008 or 2009, all of them deeper than one mile. All wells hydraulically fractured shallower than one mile reported in the database were fractured between 2010 and 2013.

To understand how different U.S. states, provinces, and countries treat aspects of hydraulic fracturing depth and groundwater protection, we also compared regulations related to well construction and groundwater protection. We reviewed regulations from all 12 states that had at least 50 wells drilled to depths shallower than one mile (Alabama, Arkansas, California, Colorado, Kansas, New Mexico, Oklahoma, Pennsylvania, Texas, Utah, Virginia, and Wyoming). We did not examine individual permits, which may have more stringent requirements that are more closely tailored to the geology or hydrology of an oil or gas field. We also reviewed select field rules in some of the states where regulations differ across counties but could not review all field rules that might apply to the wells found across all counties in those states. We examined regulations specific to (1) Shallow wells or wells with minimum separation between groundwater and source rock; (2) Prestimulation assessments of hydrology, including baseline water testing requirements; (3) Surface casing requirements; (4) Reporting requirements or assessments of fracture lengths; and (5) Disclosure of the chemicals in hydraulic fracturing fluids. Based on these and other comparisons, we summarize typical practices in different states and provide some policy recommendations based on our FracFocus analysis.

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Table 1. Depths (ft) of Hydraulic Fracturing by Percentile and Mean for the United States Overall and for Individual U.S. States[a]

depth of hydraulic fracturing (ft)	1%	5%	10%	25%	50%	75%	90%	mean
United States	980	2740	4340	6520	8180	10640	11850	8290
Alabama	1430	1670	1700	1790	1980	2830	2890	2210
Arkansas	1780	2130	2430	3190	3890	4810	5830	4120
California	1050	1430	1480	1750	2090	2920	7000	2960
Colorado	2020	5130	6270	7040	7580	8120	9000	7550
Kansas	1320	2740	4260	4710	4910	5240	5440	4910
Louisiana	7380	9980	11 020	11 590	12 010	12 460	12 950	11 950
Montana	4950	7160	7770	9190	10 030	10 340	10 460	9530
New Mexico	1760	2640	3980	5340	6930	8210	9480	6850
North Dakota	7820	8500	9180	10 090	10 530	10 850	11 110	10 370
Ohio	3670	6150	6870	7600	7940	8180	8570	7810
Oklahoma	3000	4400	4910	5350	8390	11880	12990	8560
Pennsylvania	4350	5300	5550	6210	7060	7980	8490	7040
Texas	880	3270	4690	6910	9260	10 930	11 900	8750
Utah	4580	5530	5840	6420	8500	9710	10 830	8360
Virginia	2110	2400	2570	4430	4870	5220	5700	4720
West Virginia	5500	5900	6100	6450	6810	7350	7660	6870
Wyoming	1500	1840	2040	6480	10430	13110	14200	9390

[a]Median values correspond with the 50th percentile. The number of observations in each row are United States (42 388); Alabama (55); Arkansas (1473); California (918); Colorado (5261); Kansas (206); Louisiana (1111); Montana (268); New Mexico (1292); North Dakota (2748); Ohio (157); Oklahoma (2194); Pennsylvania (2794); Texas (20 267); Utah (1692); Virginia (91); West Virginia (278); Wyoming (1583).

RESULTS AND DISCUSSION

Occurrence of Shallow Hydraulic Fracturing. Across the United States, the depths of horizontal drilling and hydraulic fracturing ranged from deeper than 3 mi (5 km) to as shallow as ~100 ft (30 m) (Table 1 and Figure 1). Out of the ~44 000 hydraulic fracturing observations in the national database, 84% of the wells were a mile or more underground, for a total of 36 600 observations. The median depth of hydraulic fracturing was 8180 ft (2490 m) and the mean depth was 8290 ft (2525 m). Approximately 25% of the hydraulic fracturing operations were deeper than two miles and the 90th percentile of the depth observations was 11 900 ft (3610 m).

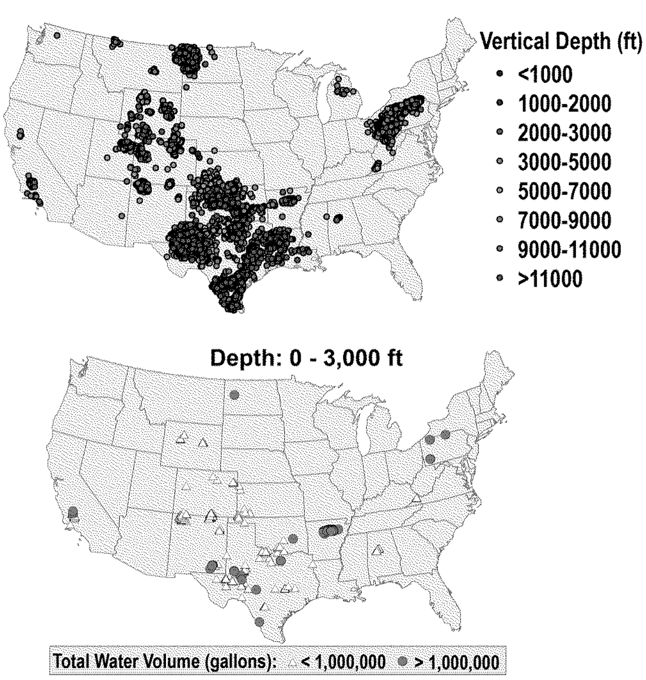

Figure 1. Map of ~44 000 hydraulic fracturing locations and depths (ft) reported to FracFocus between 2008 and 2013 (upper panel) and the subset of locations where hydraulic fracturing occurred <3000 ft and less than or greater than 1 000 000 gallons for hydraulic fracturing (lower panel). The number of locations for hydraulic fracturing <3000 ft include >300 sites in Arkansas, all of which used >1 000 000 gallons.

Although most of the observations in the database were a mile or more underground, a surprising number of hydraulic fracturing cases occurred within a mile of the surface (Figures 1 and 2). A total of 6896 wells were hydraulically fractured shallower than one mile, comprising 16% of all observations in the database. Within 3000 ft (900 m) of the surface, 2600 wells (6%) were hydraulically fractured, particularly in Texas (850 wells), California (720), Arkansas (310), and Wyoming (300). Within 2000 ft of the surface, 1268 wells or 3% of the total reported were hydraulically fractured, all of them since the year 2010, and 532 wells were fractured less than 1000 ft underground (1.3%).

The distribution of shallower hydraulically fractured wells differed substantially across states (Table 1, Figures 1 and 2). Twelve states had 50 or more hydraulically fractured wells within one mile of the surface. Texas had the most, 2872 wells that comprised 42% of all such observations nationally. Three other states, Arkansas (1224), California (804), and Oklahoma (502), had more than 500 cases of hydraulic fracturing within a mile of the surface. Eight additional states had more than 50 observations: Wyoming (389), New Mexico (314), Colorado (287), Kansas (161), Pennsylvania (135), Virginia (70), Utah (55), and Alabama (55).

States also varied in the percentage of hydraulically fractured wells shallower than a mile within their borders (Figure 3). Although Texas had the most shallowly fractured wells (2872), most of its wells (86%) were deeper than one mile. In contrast, California (804) and Arkansas (1224) had almost all of their hydraulically fractured wells within a mile of the surface, 88% and 85%, respectively. According to the FracFocus database, three additional states also had most of their fractured wells

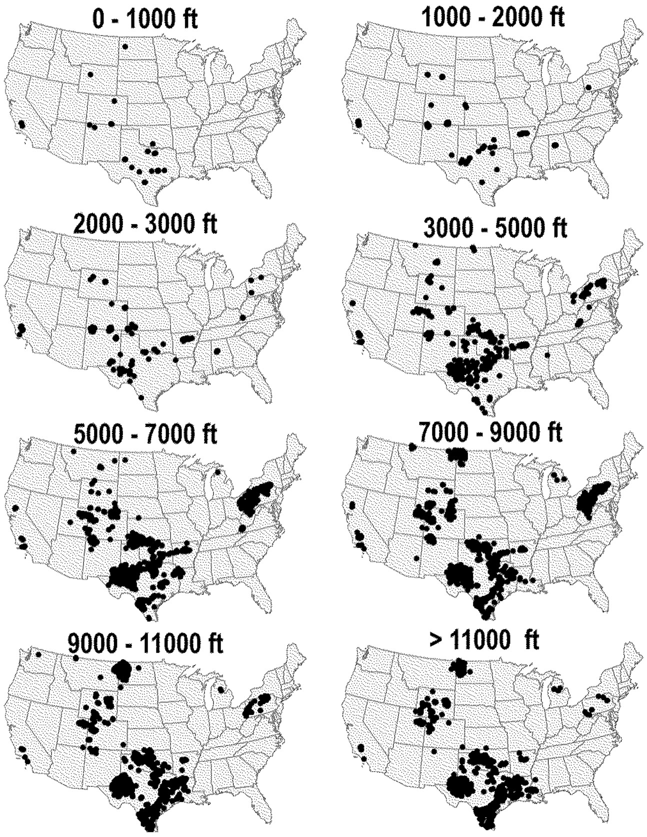

Figure 2. Location of hydraulic fracturing wells across the United States by depth increment (ft).

within a mile of the surface: Alabama (100%), Kansas (78%), and Virginia (77%). Most of the wells in Alabama and Virginia were hydraulically fractured to produce coal bed methane.

Water use for hydraulic fracturing varied widely among states (Table 2). The average water volume used to hydraulically fracture a well in the United States was 2 400 000 gallons (9 200 000 L) (Table 2). Five states with the highest reported water use per well between 2010 and 2013 were Arkansas (5 200 000 gallons), Louisiana (5 100 000 gallons), West Virginia (5 000 000 gallons), Pennsylvania (4 500 000 gallons), and Ohio (4 300 000 gallons). States with the lowest average water use for hydraulic fracturing included Alabama (38 000 gallons per well), Virginia (42 000 gallons), California (158 000 gallons), and Utah (382 000 gallons).

A subset of oil and gas wells across the United States were both shallow and water intensive. Slightly more than 2,000 wells (~5% of the data set) were hydraulically fractured shallower than one mile using >1 million gallons of water. These wells were located primarily in Arkansas (1215), Oklahoma (325), Pennsylvania (125), Kansas (105), and Texas (100). Focusing on an even shallower subset, 350 wells (~1% of data) were fractured <3,000 ft and with >1,000,000 gallons, primarily in Arkansas, but with additional wells in New Mexico, Texas, Pennsylvania, and California.

The three states with the most frequent shallow hydraulic fracturing, Arkansas, Texas, and California, provide a contrast in the practices used. Of the 1451 Arkansas wells in the FracFocus database, 314 of them (22%) were hydraulically fractured above 3000 ft and 49 (3%) were fractured between 1000 and 2000 ft, all of them after January of 2011. Surprisingly, the volumes of water and chemicals used for shallower hydraulic fracturing were indistinguishable from those used for deeper wells. The average volume of water used to hydraulically fracture Arkansas wells between 1000 and 2000 ft depths was 5.0 million gallons, compared with 5.1 million gallons between 2000 and 3000 ft and 5.3 million gallons for all AR wells deeper than 3000 ft. High-volume hydraulic fracturing is occurring at all depths in

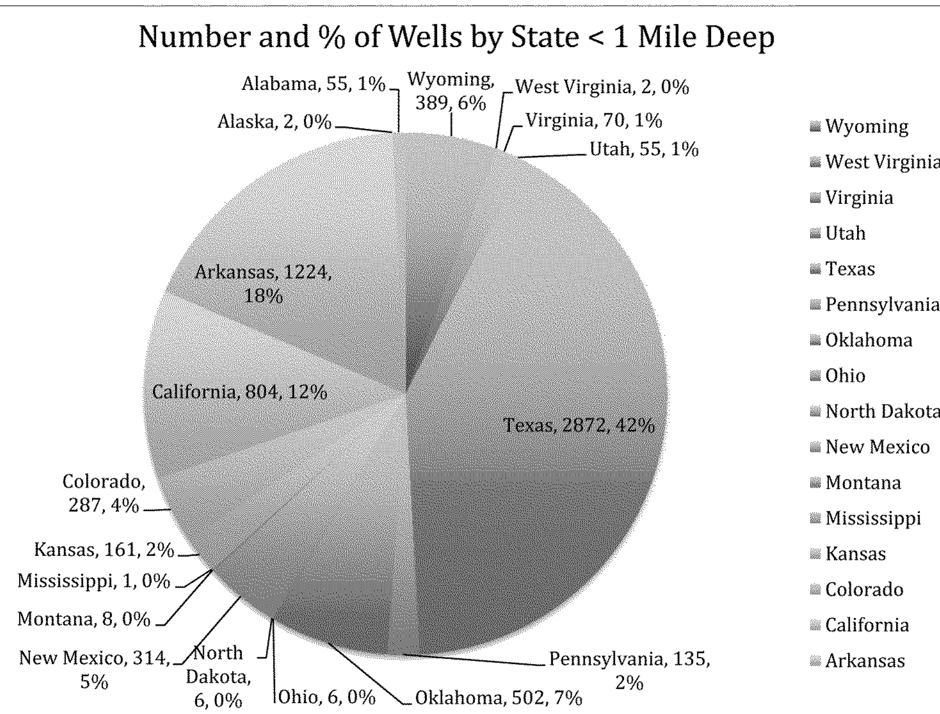

Figure 3. Number of cases of hydraulic fracturing in the United States that occurred shallower than one mile categorized for different states (n and % of all shallow wells in the United States that occurred in that state).

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Table 2. Water Use (Gallons) For Hydraulic Fracturing by Percentile and Mean for the United States Overall and for Individual U.S. States[A]

hydraulic fracturing water use (gallons)	1%	5%	10%	25%	50%	75%	90%	Mean
United States	7 170	27 400	70 800	327 000	1 520 000	3 830 000	6 020 000	2 430 000
Alabama	NA	NA	25 000	31 200	37 700	42500	47 800	37 600
Arkansas	1 300 000	2 710 000	3 290 000	4 100 000	5 310 000	6 360 000	7 160 000	5 230 000
California	11 500	18 900	22 000	48 500	77 600	184 000	287 000	158 000
Colorado	20 900	106 000	148 000	270 000	487 000	2 120 000	3 160 000	1 410 000
Kansas	NA	NA	11 400	54 800	1 500 000	1 850 000	2 230 000	1 230 000
Louisiana	39 800	247 000	1 530 000	3 620 000	5 100 000	6 640 000	7 970 000	5 140 000
Montana	NA	NA	377 000	919 000	1 520 000	2 370 000	2 960 000	1 650 000
New Mexico	5710	23 000	36 700	90 300	177 000	783 000	1 870 000	706 000
North Dakota	20 100	631 000	977 000	1 360 000	2 040 000	2 670 000	3 330 000	2 170 000
Ohio	NA	NA	2 930 000	3 520 000	4 050 000	4 680 000	5 440 000	4 310 000
Oklahoma	19 800	100 000	914 000	1 770 000	2 490 000	4 830 000	7 430 000	3 430 000
Pennsylvania	155 000	1 280 000	2 440 000	3 200 000	4 300 000	5 550 000	6 860 000	4 460 000
Texas	10 300	20 200	53 000	356 000	1 410 000	3 950 000	6 140 000	2 490 000
Utah	15 700	37 800	78 400	122 000	313 000	475 000	767 000	382 000
Virginia	NA	NA	13 000	25 800	33 000	39 100	49 500	42 100
West Virginia	NA	NA	2 560 000	3 820 000	4 980 000	6 190 000	7 290 000	5 040 000
Wyoming	4,980	5510	5710	69 400	323 000	1 100 000	2 020 000	793 000

[A] Median values correspond with the 50th percentile. When a state has fewer than 500 reported observations, the 1% and 5% numbers are omitted in the table below because of small sample sizes. The number of observations in each row are United States (42 388); Alabama (55); Arkansas (1473); California (918); Colorado (5261); Kansas (206); Louisiana (1111); Montana (268); New Mexico (1292); North Dakota (2748); Ohio (157); Oklahoma (2194); Pennsylvania (2794); Texas (20 267); Utah (1692); Virginia (91); West Virginia (278); Wyoming (1583).

Arkansas, even in the shallowest wells, with a full suite of chemicals (SI Table 1).

In contrast, although Texas had 541 cases (22%) of hydraulic fracturing within 1000 ft of the surface and 841 of 2483 cases (34%) within 3000 ft, the use of high-volume hydraulic fracturing in shallower wells was rare there. Only 10 of the 841 cases of hydraulic fracturing within 3000 ft of the surface in Texas used >1 000 000 gallons of water per well. Instead, most wells had reported volumes of <25 000 gallons for the shallowest hydraulic fracturing. Only 24 cases of hydraulic fracturing within 3 000 ft of the surface in Texas reported using more than half a million gallons of water and chemicals.

The volumes of water used for shallow hydraulic fracturing in California were also lower on average than in Arkansas. California operators reported 426 hydraulically fractured wells above 2 000 ft and 717 above 3 000 ft. Of these wells, only two were hydraulically fractured using >1 000 000 gallons of water, with 200 more wells using between 100 000 and 1 000 000 gallons.

Typical practices differ substantially across other states. Operators in Louisiana reported more than a thousand cases of hydraulic fracturing, none of them shallower than one mile. Only 15 wells in Kansas were hydraulically fractured above 3000 ft, with a maximum water volume of 110 000 gallons. In contrast, Colorado had 77 wells hydraulically fractured between 1000 and 3000 ft that used between 100 000 and 900 000 gallons per well. New Mexico had 16 wells that employed high-volume hydraulic fracturing (1.1−3.4 million gallons) between 2000 and 3000 ft and another 13 wells that used more than 100 000 gallons between 1400 ft and 3000 ft depths.

Because of the limited reporting of data to FracFocus in many states, the number of cases of shallow hydraulic fracturing reported here underestimates the actual number of cases. A number of states have relatively shallow formations that are active in shale gas production but for which data are not reported to FracFocus. The Antrim Shale is a Late-Devonian formation that covers ~40 000 mi^2 of Michigan's Lower Peninsula and lies 500−2200 ft below the surface.[22,23] As of 2010, ~12 000 wells in Michigan had been hydraulically fractured, and ~10 000 wells are in production from the Antrim Shale at depths of 500 to 2000 ft, most of them from vertical rather than horizontal wells. The New Albany Shale covers ~44 000 mi^2 of the Illinois Basin and is found in southeastern Illinois, southwestern Indiana, and northwestern Kentucky.[23] The depth of the target shale layer in the formation is 500−2000 ft. The depth to treatable drinking water is ~400 ft, leaving a gap of only 100−1600 ft between target formation and potential water layers, and ignoring any upward propagation of the hydraulic fractures.

Shallow hydraulic fracturing has also occurred in areas with ongoing controversies of potential water contamination. A review of well stimulation records in the Pavillion, WY field shows that hydraulic fracturing occurred in underground sources of drinking water (USDW) as shallowly as 1060 ft (323 m) and acid stimulation occurred as shallowly as 699 ft (213 m) below ground surface. Domestic water wells in the same area extend to at least 750 ft (229 m) belowground.[24,25] A lack of vertical separation between fracturing and drinking water increases potential hydraulic connectivity and the likelihood of groundwater contamination.[4,24]

A recent report by the California Council on Science and Technlogy[26] also highlighted the extent of shallow hydraulic fracturing in California. The report documented hundreds of hydraulically fractured wells in the San Joaquin Valley ranging in depth from 150 ft to 2000 ft. In fact, approximately half of all hydraulically fractured wells in California were within 2000 ft (610 m) of the surface. In some cases the shallower wells appear to have been hydraulically fractured into USDWs of less than 1500 mg/L total dissolved solids,[26] an issue that is important nationally, as well.

National Designations for Groundwater Protection. Two federal aquifer designations have been established to

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protect groundwater from underground injection of fluids in the United States. Pursuant to requirements to protect groundwater in the Safe Drinking Water Act (SDWA), the EPA defined a USDW in 40 CFR, Section 144.3 as an aquifer or part of an aquifer that supplies any public water system, or that contains a sufficient quantity of groundwater to supply a public water system and currently supplies drinking water for human consumption, or that contains fewer than 10 000 mg/L of total dissolved solids (TDS) and is not an exempted aquifer. To protect groundwater on land or mineral rights owned by the federal government, the Bureau of Land Management (BLM) defined "usable water" in 43 CFR 3160 BLM Onshore oil and Gas Order No. 2 as water containing up to 10 000 mg/L TDS. With the exception of injection of diesel fuel, the Energy Policy Act of 2005 explicitly exempted hydraulic fracturing from the SDWA and, hence, protecting USDWs from this process. In March of 2015, the BLM finalized regulations for hydraulic fracturing that define the extent of protection for usable water on federal lands. As discussed above, hydraulic fracturing has already occurred directly into USDWs consisting of sandstone and shale units.[24,26]

In many coal-bed methane (CBM) producing regions, relatively low-volume hydraulic fracturing for shallow vertical wells has occurred directly into USDWs.[27] CBM production in the United States began in the early 1980s and occurs from 12 primary coal basins, with the San Juan (CO, NM), Powder River (WY, MT), and Black Warrior (AL) Basins accounting for 75% of CBM production in the United States.[28] In the San Juan Basin, CBM wells vary in depth from 550 to 4000 ft, with hydraulic fracturing occurring in the northern portion in USDW with TDS values of 300−3000 mg/L.[27] In the Black Warrior Basin of Alabama, CBM wells vary in depth from 350−2500 ft, with hydraulic fracturing occurring into USDWs in portions of the Pottsville Formation. In the Powder River Basin, CBM wells are as shallow as 450 ft, although hydraulic fracturing is not widely used because of high coal-bed permeability.[27]

CBM production in Australia and Canada also sometimes occurs directly into USDWs. In Queensland, Australia, CBM wells are typically between 650 and 3300 ft deep, with TDS levels of produced water ranging from <200 mg/L to >10 000 mg/L.[29] In Alberta, Canada, most CBM development comes from water-sensitive "dry" coals in which N_2 and other gases are typically used for well stimulation, sometimes even shallower than 650 ft, using small amounts of water.[30,31] CBM recovery from "wet" coals in Alberta typically occurs within aquifers where water-based hydraulic fracturing fluids are used.[30]

Injection wells are another way that hydraulic fracturing fluids and waste waters have the potential to reach USDWs. In 2004 the EPA[27] examined the injection of hydraulic fracturing fluids into USDWs and acknowledged likely groundwater contamination due to (1) high injection pressures forcing fracturing fluids deep into secondary natural fractures (leakoff) beyond the capture zone of production wells, (2) entrapment of fracturing fluids in induced fractures upon subsidence of stimulation pressure (check-valve effect), and (3) lack of full recovery of viscous linear and cross-linked gels in the capture zone of production wells. The EPA[27] also estimated point of injection concentrations for BTEX (benzene, toluene, ethylbenzene, and xylenes) compounds and stated that dilution, adsorption, and biodegradation in USDWs would reduce contaminant concentrations to safe levels prior to impacting domestic wells, which are generally shallower than CBM wells. Based on these assumptions and a perceived lack of documented impact to domestic wells, EPA concluded that hydraulic fracturing posed little or no threat to USDWs.[27] The report did not assess fate and transport issues using analytical or numerical mathematical modeling, as would typically be required under the U.S. Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The report also did not acknowledge the greater well densities typical of shallow stimulation, where time and radial distance for dilution and degradation are sometimes minimal. In an apparent reversal of this position, EPA[32] recently stated that direct injection of fluids into or above a USDW posed an immediate risk to public health because it can directly degrade groundwater quality.

Policy Comparisons and Recommendations. National, provincial, and state policies differ for practices associated with shallow hydraulic fracturing. Germany's current administration has proposed to allow hydraulic fracturing only if it occurs below 3000 m (~10 000 ft). British Columbia takes a different approach, requiring a special permit if hydraulic fracturing is to occur above 600 m depth (S21; http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/282_2010#section21).

For the United States, only Texas and Colorado appear to have special requirements and/or or permits for shallow hydraulic fracturing. Texas prescribes a different casing and cementing process and additional pressure tests and cement evaluations (Rule §3.13; 2014) for hydraulically fractured wells: (1) with less than 1000 feet of vertical separation from the base of usable-quality waters, typically defined by the state as having <3000 mg/L total dissolved solids; (2) where the director of the Oil and Gas Division of the Texas Railroad Commission has determined that the separation is inadequate; or (3) "where the director has determined it is a structurally complex geologic setting". Colorado has a policy targeting stimulation at depths of 2000 feet or less rather than focusing on separation between usable groundwater and the hydrocarbon-bearing formation. Colorado requires additional geological, hydrogeological, and engineering assessments, based on which the Colorado Oil and Gas Conservation Commission may increase cementing requirements or limit stimulation. In contrast, states such as Arkansas, California, and Wyoming do not impose standards tailored to wells with a minimum separation from groundwater or wells that will be hydraulically fractured at shallow depths, instead regulating all wells the same regardless of depth.

The assumption of adequate vertical separation between hydraulic fracturing and drinking water aquifers is further embedded in most state rules that address risk primarily through casing and cementing requirements, rather than through limitations on vertical separation between the protected groundwater and the target formation or through additional requirements for shallow wells. All states that we reviewed have a general performance standard requiring oil and gas operations to protect groundwater. Protected groundwater is most often defined by suitability for use, which typically uses salinity as part of the standard. Some states require operators to include information about the known protected groundwater in drilling applications or completion reports. Alabama, California, and Colorado all require operators to conduct a groundwater assessment before hydraulic fracturing occurs, within a radius specified differently by state.

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The states that we reviewed vary widely in their surface casing technical standards. New Mexico and Utah were the only states in our review that rely solely on the general performance standard for protection of groundwater and do not have minimum casing depths. The remaining 10 states in our review require minimum surface casing depths or require surface casing to be set some distance below the deepest protected groundwater or a combination of both. In Virginia, operators are required to install surface casing either to at least 300 ft depth or to 50 ft below the deepest useable groundwater, whichever is deeper (4VAC25−150−530). In Wyoming, surface casing must be set below all known useable groundwater and at a minimum of 100 ft below any permitted water supply wells within a quarter mile of the oil or gas well (WCWR 055−000−003 (2015)). Alabama varies the minimum surface casing depth based on the true vertical depth of the well. For wells with a true vertical depth of less than 4000 feet, the minimum surface casing depth is 300 feet (Alabama Administrative Code r.400−1−4−.09 (2014)). Arkansas, Kansas, and California, among other states, set minimum casing depths by county in individual oil and gas fields. These field rules vary across each state and are designed to incorporate field-specific geological and hydrological conditions. Arkansas has a wide range of casing depths that are set by state regulation or rules specific to individual fields. In the Fayetteville Shale, for example, wells drilled after June 1, 2011 must set surface casing at least 500 feet below the lowest surface elevation within one mile of the well, with a minimum of 1000 feet of surface casing cemented to surface (178−00 Arkansas Code R. § 001:B-15 (2015)).

All of the 12 states that we reviewed require operators to assess well drilling and completion and to submit completion reports to the regulatory agencies within a few months of hydraulic fracturing. The assessments include cement evaluation as well as drilling depth and hydraulic fracturing treatment information. Some states also require information on fracture propagation. Arkansas, California, and Wyoming require operators to report estimated fracture lengths in the completion report or the completion design report. Arkansas operators are also required to report the calculated design fracture length and the estimated true vertical depth to the top of the fracture after stimulation occurs (178−00 Arkansas Code R. § 001:B-19 (2015) AR Rule B-19). Wyoming and California require operators to report estimated fracture lengths, but do not request information about the true vertical depth of the fractures. Alabama requires estimated length and orientation of fractures to be submitted for approval by the oil and gas board as part of the hydraulic fracturing plan, which is submitted prior to hydraulic fracturing.

Disclosure rules for hydraulic fracturing chemicals also make no distinction between fracturing that occurs near the surface or deep underground. In general, most states now require disclosure of the names and CAS (Chemical Abstract Service) numbers of chemicals used in hydraulic fracturing, although typically with exemptions for trade secrets.[4,8] A few states such as California also require disclosure of chemical concentrations. Many cases of shallow hydraulic fracturing in the FracFocus database used little water (<25 000 gallons) and, in consequence, far smaller volumes of chemicals than high-volume hydraulic fracturing. Some of the shallowest cases also applied nitrogen as the primary agent of hydraulic fracturing, using N_2 either alone or as a foam, with smaller amounts of water used to deliver chemicals and proppants such as sand. Nevertheless, there appear to be no additional requirements for chemical disclosure in any state where shallow hydraulic fracturing is occurring. In California, examples of the chemicals used in shallow hydraulic fracturing included toluene, xylene, methanol, sulfuric acid, phosphoric acid, xylenesulfonic acid, and methylene sulfonic acid.

Given the extensive use of chemicals in shallow hydraulic fracturing, particularly in states such as Arkansas (Supporting Information Table S1), California, and New Mexico where millions of gallons of fluids are being delivered in single wells, what additional best practices and policies might be beneficial? Considering this question is important because shallow hydraulic fracturing often has greater potential risks of contamination than deeper hydraulic fracturing does. One suggestion is for operators to provide more information about fracture length, true vertical depth to the top of fractures, and distance between groundwater resources and potential fractures. Another is for states to assess what additional safeguards should apply for hydraulic fracturing shallower than 3000 ft based on the geologic and hydrologic data in specific oil and gas fields. A third recommendation is for a mandatory state or federal registry for all hydraulic fracturing occurring shallower than 3000 ft. Such a registry would allow people to track the locations, depths, and volumes of chemicals used around them. Requiring full chemical disclosure · without trade secret exemptions · for all chemicals used in hydraulic fracturing above 3000 ft would enhance transparency and public confidence but would undoubtedly be controversial. Finally, because shallow hydraulic fracturing places people and drinking water aquifers at potentially greater risk than deeper fracturing does, predrilling and post- stimulation water testing for all homeowners on private water wells within 2500 horizontal feet of the oil or gas well or to a radius at least 1000 ft beyond the greatest extent of horizontal drilling from the oil or gas well, whichever is greater, would provide additional assurance that shallow hydraulic fracturing is not impacting drinking water reservoirs and would provide additional information needed for effective regulation. This proposed change would not alter predrilling sampling in the majority of cases because many shallow wells within a few thousand feet of the surface are vertically fractured. Only in cases of shallow horizontal drilling and high-volume hydraulic fracturing would the greater safeguard distances apply.

In summary, our analysis suggests that additional safeguards would be beneficial if shallow hydraulic fracturing continues in the future. Few states provide additional oversight or data transparency regardless of how shallow the fracturing occurs, even for high volume hydraulic fracturing. To protect people, the social license to operate for companies, and current and future sources of drinking water, the possibility of contamination from shallow hydraulic fracturing should be acknowledged in the best practices and rules governing it.

ASSOCIATED CONTENT

* Supporting Information

A table of all chemicals used for hydraulic fracturing in Arkansas shallower than 2000 ft reported to FracFocus (Table S1). The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01228.

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Notes

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